

LX Cygni: A carbon star is born[★]

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ABSTRACT

Context. The Mira variable LX Cygni (LX Cyg) has shown a dramatic increase of its pulsation period in the recent decades and is appearing to undergo an important transition in its evolution.

Aims. We aim to investigate the spectral type evolution of this star over recent decades as well as during one pulsation cycle in more detail and discuss it in connection with the period evolution.

Methods. We present optical, near- and mid-infrared low-resolution as well as optical high-resolution spectra to determine the current spectral type. The optical spectrum of LX Cyg has been followed for more than one pulsation cycle. We compare recent spectra to archival spectra to trace the spectral type evolution, and we analyse a Spitzer mid-IR spectrum for the presence of molecular and dust features. Furthermore, the current pulsation period is derived from AAVSO data.

Results. We found that the spectral type of LX Cyg changed from S to C sometime between 1975 and 2008. Currently, the spectral type C is stable during a pulsation cycle. We show that spectral features typical of C-type stars are present in its spectrum from ~ 0.5 to $14\ \mu\text{m}$, and attribute an emission feature at $10.7\ \mu\text{m}$ to SiC grains. Within only 20 years, the pulsation period of LX Cyg has increased from ~ 460 d to ~ 580 d and is stable now.

Conclusions. We conclude that the change in spectral type and increase in pulsation period happened simultaneously and are causally connected. Both a recent thermal pulse (TP) and a simple surface temperature decrease appear unlikely to explain the observations. We therefore suggest that the underlying mechanism is related to a recent third dredge-up mixing event that brought up carbon from the interior of the star, i.e. that a genuine abundance change happened. We propose that LX Cyg is a rare transition type object that is uniquely suited to study the transformation from oxygen- to carbon-rich stars in detail.

Key words. stars: AGB and post-AGB – stars: evolution – stars: carbon – stars: individual: LX Cyg

1. Introduction

Mira variables are red giant stars thought to be in the asymptotic giant branch (AGB) phase of evolution. In this phase, important changes happen in the star due to the addition of nucleosynthesis products to its atmosphere by a deep mixing process called the third dredge-up (3DUP). Most notably, carbon (^{12}C) is added, which has a major impact on the molecular equilibrium in the cool outer layers of the star. The crucial parameter determining the appearance of the star's spectrum is the ratio of the number of oxygen to carbon atoms. Most of O and C are locked up in carbon monoxide (CO), and the more abundant of these elements forms other molecules that dominate the spectrum. Metal oxides (TiO, VO), in the case of an excess of oxygen, form the spectral bands typical of M-type stars, whereas carbon-bearing molecules (CN, C_2 , C_2H_2) form in carbon-rich stars of type C. The star is of intermediate spectral type (MS, S, SC) as the C/O

ratio increases towards unity; see Gray & Corbally (2009) for details of spectral classification of late-type giants. Thus, the sequence M – MS – S – SC – C is thought to reflect an evolutionary path that a star takes on the AGB. It is known that due to the pulsation, Mira variables change their spectral subtype within the main spectral types because of temperature variations along a pulsation cycle (Terror, 1969). True spectral type changes are rare. Only a few examples have been claimed, and one of those is BH Cru (Whitelock, 1999). This star seems to have changed its spectral type from SC to C (Lloyd Evans, 1985) with little cyclical variation after the change (Lloyd Evans, private communication). Alternative explanations have been put forward that do not require a genuine chemical abundance change (Zijlstra et al., 2004).

Also, most Mira variables have pulsation periods that are more or less stable over decades to centuries. Templeton et al. (2005) investigated light curves of 547 Miras with a long baseline of visual observations. Eight Miras were found to have changed their pulsation periods systematically at the significance level of 6σ or greater, either increasing or decreasing, in the past decades. Further candidates for stars with changing pulsation periods were presented by Lebzelter & Andronache (2011). The mechanism usually put forward to explain the changing pulsation period is the violent ignition of the dormant He-burning

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shell during a so-called thermal pulse (TP) or He-shell flash (Wood, 1975). The radius of the star changes in reaction to the changed energy supply (surface luminosity) during the TP, which in turn affects the pulsation period (Vassiliadis & Wood, 1993). In the aftermath of a TP, a 3DUP event may occur when the convective envelope deepens to reach stellar layers where nuclear processing has taken place before. In this way, a 3DUP event is intimately connected to a TP.

The star with the strongest period increase in the sample of Templeton et al. (2005) is LX Cygni (LX Cyg). This star is very similar to BH Cru in that both underwent a large period increase and were classified as S/SC type before the period increase. After its period increase, BH Cru was observed to be a C-type Mira (Whitelock, 1999). In this paper, we report spectral observations of LX Cyg to analyse its current spectral type and spectral type evolution during recent decades. We demonstrate that with respect to the spectral type after the period increase both BH Cru and LX Cyg also show the same behaviour, which is probably the result of the same underlying physical processes.

This paper is structured in the following way. In Sect. 2 the observations are presented. Section 3 first analyses the period evolution of LX Cyg (Sect. 3.1) before continuing with the spectral analysis, both for the current spectral type (Sect. 3.2) as well as its spectral type evolution (Sect. 3.5). The results are discussed in Sect. 4, and conclusions are drawn in Sect. 5.

2. Observations

We based this study on the experience with BH Cru (Whitelock, 1999; Uttenthaler et al., 2011), a Mira that exhibited a period increase similar to that of LX Cyg along with a change of spectral type from S/SC to C. As a starting point of this study, we obtained a high-resolution optical spectrum of LX Cyg to investigate its current spectral type. The spectrum was obtained with the Hermes fibre-fed spectrograph (Raskin et al., 2011) at the 1.2 m Mercator telescope on the island of La Palma, Spain, in high-resolution mode ($R = 85\,000$). Two exposures of 1800 s integration time each were taken on 24 August 2011, covering the wavelength range 377 – 900 nm. However, shortwards of 500 nm the flux is essentially zero in these spectra. This spectrum is presented and discussed in Fig. 3; see Sect. 3.2.

Because of claims that the change in spectral type from SC to C could be due to a temperature decrease in the atmosphere rather than a true change in chemical composition (Zijlstra et al., 2004), we monitored LX Cyg with low-resolution optical spectroscopy over about one pulsation cycle, i.e. between 28 November 2011 and 13 August 2013. The aim of these observations was to see if the spectral type depends on the pulsation phase. The observations were obtained with the 0.8 m Cassegrain telescope of the Vienna University Observatory (VUO) and a DSS-7 spectrograph manufactured by SBIG. The DSS-7 grating spectrograph provides for a maximum dispersion of ~ 0.55 nm/pixel, corresponding to a spectral resolving power of $R \approx 500$. With this camera, the wavelength coverage is approximately 480 – 820 nm. At each observing date, several exposures of LX Cyg of 300 s integration time were obtained, but here only the individual spectra with the highest signal-to-noise ratio are presented. Care was taken to position the slit such that no nearby star contaminated the spectrum of the target. Other than LX Cyg, known SC-type stars such as FU Mon, CY Cyg, GP Ori, and R CMi, were obtained with the same instrument for comparison. These data are discussed in more detail in Sects. 3.2 and 3.4.

Table 1. Data of our spectral observations

Date dd/mm/yyyy	Instrument	Res. power $R = \lambda/\Delta\lambda$	Wavelength (nm)
24/08/2011	Hermes/Mercator	85 000	$\sim 377 - 900$
28/11/2011	DSS-7/VUO	500	$\sim 450 - 858$
20/12/2011	DSS-7/VUO	500	$\sim 450 - 856$
18/01/2012	DSS-7/VUO	500	$\sim 450 - 858$
15/06/2012	DSS-7/VUO	500	$\sim 402 - 815$
23/07/2012	DSS-7/VUO	500	$\sim 400 - 806$
14/08/2012	DSS-7/VUO	500	$\sim 405 - 815$
11/09/2012	DSS-7/VUO	500	$\sim 403 - 816$
21/10/2012	NOTCam/NOT	2 500	$\sim 830 - 2360$
16/11/2012	DSS-7/VUO	500	$\sim 408 - 820$
12/12/2012	DSS-7/VUO	500	$\sim 408 - 820$
13/08/2013	DSS-7/VUO	500	$\sim 410 - 820$

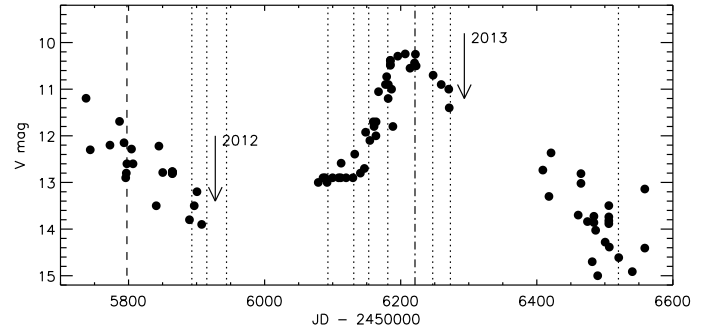


Fig. 1. Visual and V-band photometric mean AAVSO light curve of LX Cyg between JD 2455 700 and JD 2456 600. The dashed line indicates the time of the Hermes/Mercator high-resolution observations, the dash-dotted line the NOTCam near-IR observations, and the dotted lines the optical low-resolution observations at the Vienna University Observatory. Arrows denote 1 January 2012 and 2013.

On 21 October 2012, we also obtained $R = 2500$ spectra with NOTCam (Abbott et al., 2000) at the Nordic Optical Telescope on the island of La Palma, Spain, covering the range $\sim 820 - 2360$ nm. These observations were motivated by the fact that LX Cyg was observed by Joyce et al. (1998) at low resolution in the J-band in 1994; our spectra provide for a check of the spectral changes that might have happened between 1994 and 2012. The data are also useful to compare with other observations from the literature. See Sects. 3.2 and 3.5 for a discussion of these data. Table 1 lists all the important information of our spectral observations.

Figure 1 shows the AAVSO¹ visual light curve of LX Cyg, for the time span in which we obtained spectral observations, to indicate the visual phase. The data points are 10-day means of visual and V-band photometric observations. There is no systematic shift between the visual estimates and V-band observations, so they were averaged, as either of them alone would trace the light curve insufficiently. In total, the spectral observations span more than one pulsation cycle.

Finally, we also searched the *Spitzer* space telescope archive for observations of LX Cyg. Indeed, observations were carried out on 05 December 2008 in programme ID 50717, AOR: 27668480 (PI: M. Creech-Eakman) with the Infrared Spectrograph (IRS Houck et al., 2004). The spectrum covers the range between 5.2 and 37.2 μm by using the short-low (SL:

¹ <http://www.aavso.org/>

5.2 – 14.5 μm ; $64 < R < 128$), short-high (SH: 9.9 – 19.6 μm ; $R \sim 600$) and long-high (LH: 18.7 – 37.2 μm ; $R \sim 600$) modules. The data were retrieved from the *Spitzer* Science Center Data Archive using Leopard. The *Spitzer* IRS Custom Extractor (SPICE) was used to perform the extraction of the spectra for each nod position from the 2D images. The spectra were cleaned for bad data points, spurious jumps, and glitches, and then they were combined and merged to create a single 5–37 μm spectrum. We did not correct for flux offsets between different wavelengths ranges, but these are minor. The *Spitzer* spectrum allows for an investigation of the type of dust forming around the star; this will be discussed in more depth in Sect. 3.3 (Figs. 5 and 6).

3. Analysis and results

3.1. Period evolution

The variability of LX Cyg was first pointed out by Hoffmeister (1930). The dramatic period increase of this star was first reported by Templeton et al. (2003) and confirmed by Barzdis & Alksnis (2003) as well as Zijlstra et al. (2004). Templeton et al. (2003) analysed the AAVSO observations that commenced in 1967 and find a period increase from ~ 460 to ~ 580 d. The period increase seems to have started in 1975; the strongest growth happened between 1983 and 1995 when the period increased at a rate of ~ 7.6 d/yr. All observations prior to 1967 indicate that the period was close to ~ 460 d, suggesting that it was relatively stable, apart from cycle-to-cycle variations that are seen in many Miras of such long period.

We used AAVSO visual data to determine the pulsation period of LX Cyg between JD 2 452 000 – 2 456 626 (31 March 2001 – 30 November 2013), including eight maxima. The data were analysed with the programme `period04` (Lenz & Breger, 2005). A mean period of 588.3 d was found from these data. It appears that the period has not significantly increased since 1995. We therefore conclude that the pulsation period of LX Cyg was stable at ~ 460 d until 1975, followed by a marked period increase of nearly 25% up to 1995, when it stabilised at ~ 580 d. This means that the expansion of the star that caused the period increase has stopped by now. BH Cru showed a very similar evolution of pulsation period, although it was claimed by Zijlstra et al. (2004) that it may have had a long pulsation period a few decades before the recently observed period increase, and that its period may be intrinsically unstable.

3.2. Current spectral type

Several comparisons were done to check the current spectral type of LX Cyg to classify it among known SC- and C-type stars, and to check for any spectral differences.

In the optical spectral range, we followed the SC spectral-type criteria of Keenan & Boeshaar (1980), which are reproduced in Table 2. Bands of ZrO are present in types SC X/7, which equals SX/7, or earlier abundance types. Here, “X” refers to the temperature type. A high signal-to-noise ratio spectrum of LX Cyg obtained with the DSS-7 spectrograph at the Vienna University Observatory gives a good overview of the molecular features present in the star as well as the general flux distribution throughout the optical spectral range. The spectrum obtained on 16 November 2012 as part of our spectral monitoring campaign (Sect. 3.4) is shown in Fig. 2. On that date, LX Cyg was close to maximum visual light (Fig. 1). The main spectral features in that spectrum are labelled. Prominent bands of ZrO would be located at 555.2, 584.9, 613.6, 647.4, and 649.5 nm (Gray & Corbally,

Table 2. Classification criteria for the SC spectral types, reproduced from Keenan & Boeshaar (1980).

Spectral type	Criteria for C/O	Estimated C/O
SX/7 = SC X/7	ZrO weaker. D lines strong.	0.99
SC X/8	No ZrO or C ₂ . D lines very strong.	1.00
SC X/9	C ₂ very weak. D lines very strong.	1.02
SC X/10 = C X,2	C ₂ weak. D lines strong.	1.1:

Notes. X denotes the temperature type; D lines are Na D lines.

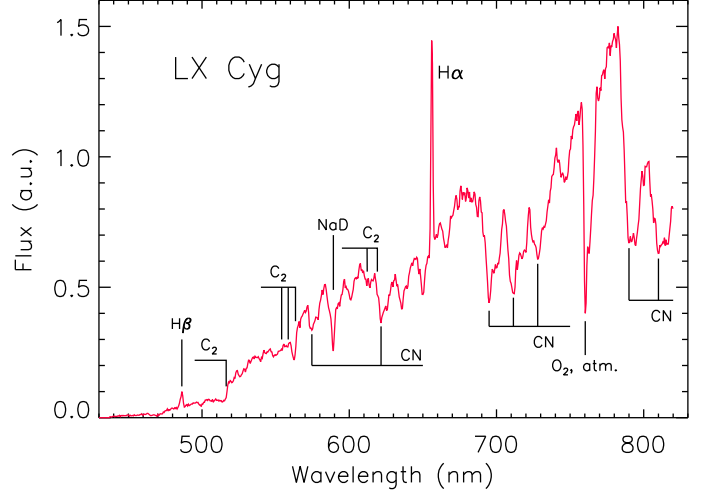


Fig. 2. Low-resolution optical spectrum of LX Cyg on 16 November 2012 with the main spectral features labelled.

2009), but they are absent. Bands of CN and C₂ dominate the spectrum. The spectra of known SC stars obtained with the same instrumentation indicates that, if at all, none of these shows such prominent C₂ bands as LX Cyg. We conclude that LX Cyg cannot be of type SX/7 or earlier abundance type.

The best distinguishing feature between the SC subtypes is the strength of the C₂ bands. To estimate their strength, we compared the Hermes spectrum to the spectral atlas of carbon stars of Barnbaum et al. (1996). The Hermes spectrum was smoothed to the resolution of the atlas spectra ($R = 2500$) for this comparison. In particular, the spectrum was compared to the N-type carbon stars RS Cyg, Z Psc, and V460 Cyg, which are presented by Barnbaum et al. (1996) to illustrate the carbon abundance scale of N-type stars; see their Fig. 1c. These three stars have C₂ indices of 3, 4, and 4.5, respectively. This comparison is shown in Fig. 3. Dotted vertical lines in that figure indicate the wavelengths of the 0 – 1, 1 – 2, and 2 – 3 band heads of the C₂ Swan system that characterise typical carbon stars (Kipper, 2004). The C₂ bands are not weak in LX Cyg. They are clearly discernible, indicating a spectral subtype of at least SC X/10, which equals C X,2 on the carbon star C/O abundance scale, or even higher abundance index. From this, one would currently not classify it as SC-type star.

A difference between LX Cyg and the atlas spectra of Barnbaum et al. (1996) is that LX Cyg seems to faint more strongly at wavelengths shorter than ~ 5700 Å than the atlas stars do. This may be caused by a higher amount of dust around LX Cyg than around the other stars. This is confirmed by the 2MASS $J - K$ colour of the stars. While RS Cyg, the reddest of the three atlas stars, has 1.885 in this colour, LX Cyg has $J - K_S = 2.199$. The other two stars are even bluer at

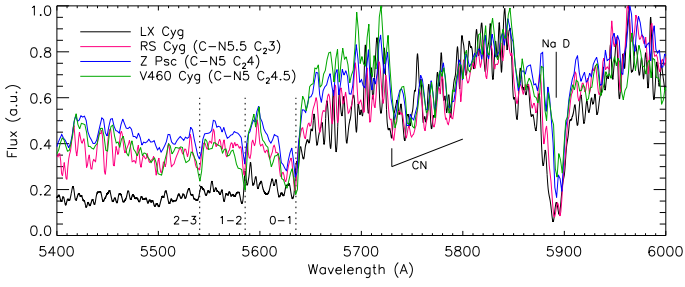


Fig. 3. Comparison between the N-type spectral standard stars RS Cyg (C-N5.5 C₂3, red), Z Psc (C-N5 C₂4, blue), and V460 Cyg (C-N5 C₂4.5, green) from Barnbaum et al. (1996) with the Hermes spectrum of LX Cyg smoothed to the resolution of the atlas spectra ($R = 2500$, black). The spectra are scaled to have the same maximum flux in the shown wavelength range. Vertical dotted lines indicate the wavelengths of C₂ band heads from the Swan system (Kipper, 2004).

$J - K_s \approx 1.52$. As we show below (Sect. 3.3), the star’s mid-IR spectrum also favours the presence of dust around LX Cyg. Among these four stars, the NaD line is indeed strongest in LX Cyg. The comparison is complicated by the fact that LX Cyg is a Mira variable with a visual amplitude of ~ 4 mag, whereas the spectral atlas stars are much less variable (semi-regular variables of type SRa and SRb).

The high-resolution Hermes spectrum was also searched for lines of heavy elements that are formed during the slow neutron-capture (s-)process in the interior of AGB stars. All the heavy-element lines that also Abia & Wallerstein (1998) detected in their high-resolution spectrum of BH Cru could be detected. Therefore, we can also conclude that LX Cyg is enriched in s-process elements and that it is a true TP-AGB star. We caution that the Hermes spectrum of LX Cyg is very complex, hence quantitative measurements are unfortunately difficult to make.

At longer wavelengths, the NOTCam spectrum of LX Cyg was compared to spectra of C- and SC-type stars identified by Wright et al. (2009). Figure 4 shows this comparison for the H band, which contains a feature at ~ 1530 nm that is probably due to C₂H₂. It appears that SC- and C-type stars differ markedly in this feature. The one SC-type star in the sample of Wright et al. (2009), the extremely red stellar object (ERSO) no. 80, shows a lack of opacity at the wavelength of this feature, compared to a flux depression in the C-type stars. The difference between the stars in the strength of this feature may be due to a difference in temperature (the feature becoming stronger at lower temperature) and/or due to a difference in composition (becoming stronger at higher C/O). Figure 4 shows that LX Cyg is very similar to two of the C-type stars, namely ERSO 119 and ERSO 136. Besides this C₂H₂ feature, also the CO $\Delta v = 3$ bands at ~ 1558 nm, ~ 1577 nm, ~ 1598 nm, etc., are clearly visible in all stars shown in Fig. 4. From this comparison, we can conclude that LX Cyg is now a C-type star.

3.3. Circumstellar environment of LX Cyg

To help analyse the *Spitzer* IRS spectrum of LX Cyg, we first inspect its spectral energy distribution (SED); see Fig. 5. Photometry was collected from Vizier², except for the fluxes in the B and V bands, for which cycle-averaged fluxes from AAVSO data have been used. The wavelength range from the

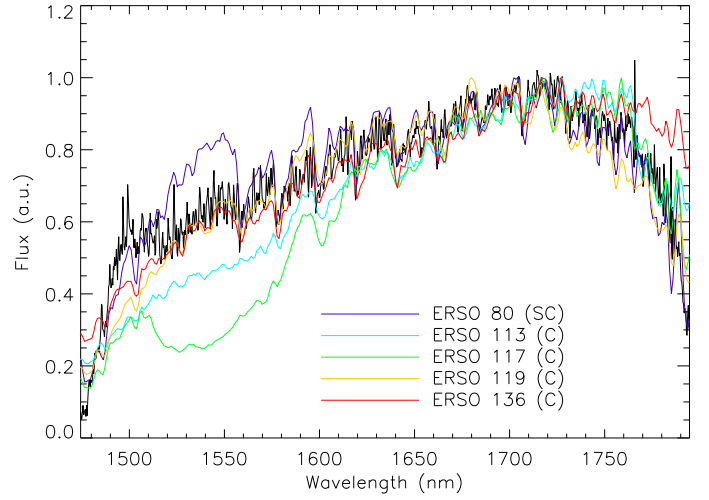


Fig. 4. NOTCam H-band spectrum of LX Cyg (black line) compared to four C-type and one SC-type star identified by Wright et al. (2009); see legend.

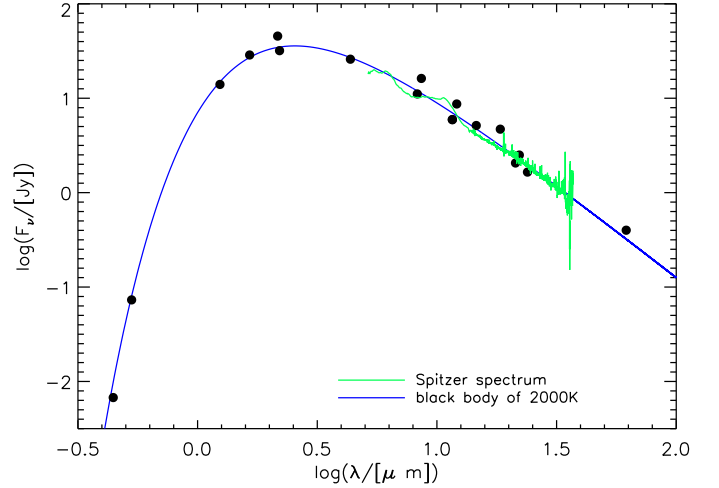


Fig. 5. Observed SED of LX Cyg (black dots). The *Spitzer* IRS spectrum is plotted in green. The blue curve is a black-body spectrum of 2000 K, scaled to have the same median flux as the *Spitzer* spectrum in the range 20 – 24 μ m.

B-band (0.444μ m) out to the IRAS 60 μ m band is covered by the SED. A black-body spectrum of a temperature of 2000 K is included in that figure (blue line). This spectrum is scaled to have the same median flux as the *Spitzer* spectrum (green line) in the range 20 – 24 μ m. The SED of LX Cyg is well represented by the 2000 K black-body spectrum.

The *Spitzer* spectrum is shown in linear scale in more detail in Fig. 6. The black-body spectrum, scaled in the same way as in Fig. 5, is an excellent fit to the spectrum at wavelengths longer than $\sim 17 \mu$ m. No dust features are visible between 17 and 37 micron. At shorter wavelengths, there are regions with an excess or a deficit of flux compared to the black body. We interpret these features with the help of an over-plotted COMARCS model spectrum of a dust-free carbon star from Aringer et al. (2009, red line). This model has the following stellar parameters: $T_{\text{eff}} = 2800$ K, $\log g [\text{cm s}^{-2}] = 0.0$, $M = 1.0 M_{\odot}$, $Z = 1.0 Z_{\odot}$, micro-turbulence $\xi = 2.5 \text{ km s}^{-1}$, and C/O=1.05. The model spectrum is scaled in the same way as the *Spitzer* and black-body spectra. The surplus flux at $\sim 9.5 \mu$ m compared to the black body

² <http://vizier.u-strasbg.fr/viz-bin/VizieR>

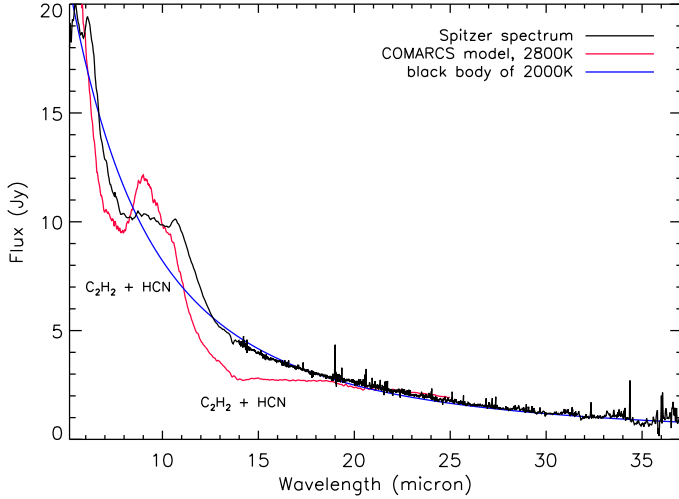


Fig. 6. *Spitzer* IRS spectrum of LX Cyg (black line). Overplotted in blue is the same black-body spectrum as in Fig. 5, as well as a scaled dust-free C-star model spectrum from Aringer et al. (2009, red line).

is not an emission component, but rather is a result of the scaling to the pseudo-continuum, not the true continuum. With this COMARCS model, we identify the flux depressions at $\sim 7\mu\text{m}$ and $\sim 14\mu\text{m}$ with blended molecular bands of $\text{C}_2\text{H}_2 + \text{HCN}$, typical of carbon stars. However, we can clearly see two main emission features peaking at $\sim 6.2\mu\text{m}$ and $\sim 10.7\mu\text{m}$. The latter agrees with a peak from SiC dust grain emission predicted by Mutschke et al. (1999), which are expected to form in carbon-rich environments. We therefore assume that this emission peak stems from SiC grains.

The peak at $6.2\mu\text{m}$ is more uncertain to interpret. It coincides with an emission feature known from polycyclic aromatic hydrocarbon (PAH) molecules, which are also expected to be formed in C-rich environments such as atmospheres of carbon stars (Allamandola et al., 1989). However, there are only a few AGB stars where mid-IR features of PAHs have been detected; see Smolders et al. (2010) for a discussion. Also, the $6.2\mu\text{m}$ feature may be expected to be accompanied by other PAH features at 7.9 , 8.6 , and $11.2\mu\text{m}$, which we cannot detect. It is unclear if the conditions can be such that only the $6.2\mu\text{m}$ feature emits. As PAH features have been detected in S as well as in C-type stars (Smolders et al., 2010, and references therein), there is not a strong discriminant between those spectral types. Non-equilibrium, shock-driven chemistry may be responsible for PAH formation via C_2H_2 at $\text{C/O} \sim 1.0$ (Cherchneff et al., 1992). Alternatively, the feature could be the result of an absorption band at $5.5\mu\text{m}$ by C_3 (Gautschi-Loidl et al., 2004). However, this would probably require a somewhat high C/O ratio, which we consider unlikely.

There are two more arguments for the presence of dust around LX Cyg. Both have their physical origin in the fact that short-wavelength photons are absorbed by dust grains and their energy is re-emitted at longer wavelengths in the mid-IR range, thereby shifting the maximum flux towards longer wavelengths. The first argument is the $J - K_S$ colour of LX Cyg. Using 2MASS photometry dated 15 June 2000, $J - K_S = 2.199$ is found for the star. This is redder than any of the 12 SC stars observed by Joyce et al. (1998), which reach 2.062 at most. It is also redder than all dust-free COMARCS C-star models of Aringer et al. (2009). On the other hand, the carbon-rich Miras

from Whitelock et al. (2006) occupy colours in the range ~ 1.6 to 6.0. With the relation between $J - K_S$ and the mass-loss rate given in Nowotny et al. (2013), we derive $\dot{M} \approx 4 \times 10^{-7} M_\odot \text{yr}^{-1}$ for LX Cyg. This mass-loss rate is relatively low among the C stars. Secondly, the temperature of 2000 K of the black-body spectrum required to approximate the SED of LX Cyg is quite low. Also, AAVSO visual and V-band observations of the past 15 years suggest that LX Cyg is becoming fainter in the optical, which suggests that more dust has recently formed around the star. This dust may not only be present in the form of SiC grains as concluded above, but may also be amorphous carbon grains that do not have any spectral features to identify them.

In summary, the circumstellar environment of LX Cyg as evidenced by mid-IR molecular and dust features detected in the *Spitzer* IRS spectrum as well as its SED, suggests a carbon-rich nature of the star.

3.4. Spectral monitoring

In the course of our spectral monitoring programme with the 0.8 m telescope at VUO, observations have been obtained on 10 dates between 28 November 2011 and 13 August 2013, spanning 624 days. The spectral evolution in this period is shown in Fig. 7. Even though some of the CN bands are weaker in the fainter phases of the cycle, this figure clearly demonstrates that LX Cyg is of stable spectral type C. The spectrum is dominated by bands of C_2 and CN. The C_2 bands are strongest at phases around visual maximum. As the star approaches maximum light, the $\text{H}\alpha$ line starts to emit. Shortly after maximum light (16 November 2012), also the $\text{H}\beta$ line is visible in emission; this spectrum is shown in more detail in Fig. 2 with the main features labelled.

3.5. When did the change in spectral type happen?

As has been shown in previous sections, LX Cyg most probably is a stable carbon star now. This leads to the question: When did the change in spectral type happen?

Table 3 collects in chronological order all spectral type determinations of LX Cyg that we found in the literature. There are at least 13 observations spanning almost 27 years, all of them reporting LX Cyg with spectral type S or SC. Terrill (1969) lists LX Cyg as showing only bands of LaO in the red ($680 - 880\text{nm}$). Blanco & Nassau (1957) report LX Cyg as being of S type with LaO bands present and being “very red”, based on the observations published by Cameron & Nassau (1956). These latter authors report that the star has an unidentified absorption band at 850nm , in addition to strong LaO bands at 740 and 790nm . C_2 lines are only weakly present at one occasion in 1978 when LX Cyg was assigned the abundance index 9 by Keenan & Boeshaar (1980); see Table 2.

After 1979, spectral observations of the star became rare. A high-resolution FTS spectrum in the K band ($\sim 1900 - 2500\text{nm}$, $R \approx 50000$) was obtained on 14 October 1984 (JD 2445987) by Dominy & Wallerstein (1987). They observe that LX Cyg is their “most difficult case” in a sample of seven S and SC stars. Unfortunately, the K band does not contain spectral features that are established for spectral (sub-)type determination of cool giants. Nevertheless, it is instructive to inspect the strength of the CN lines. We compared the archival FTS spectrum of LX Cyg obtained by Dominy & Wallerstein (1987) with high-resolution spectra of the M3S-type giant σ^1 Ori and the C5.5 carbon star X TrA obtained with CRIRES at the VLT in the CRIRES-POP programme (Lebzelter et al., 2012); see Fig. 8. In that figure,

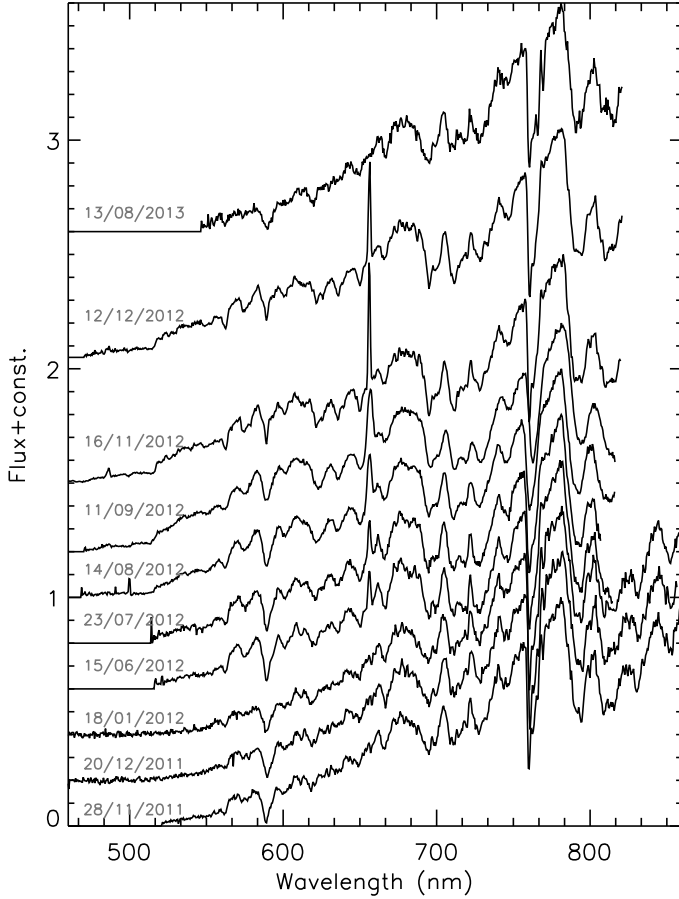


Fig. 7. Low-resolution optical spectra of LX Cyg obtained with the DSS-7 spectrograph at the 0.8 m Cassegrain telescope of the VUO in chronological order, from bottom to top.

Table 3. Historic spectral type determinations of LX Cyg.

Date dd/mm/yyyy	Sp. Type	Reference
22/10/1952	S LaO 3	Terrill (1969)
05/09/1954	S LaO 3	Terrill (1969)
20/08/1955	S	Cameron & Nassau (1956)
27/09/1956	S LaO 2-3	Terrill (1969)
05/10/1957	S LaO 2	Terrill (1969)
12/09/1958	S LaO 2:	Terrill (1969)
07/06/1962	S LaO 3	Terrill (1969)
03/10/1965	S LaO 1	Terrill (1969)
27/08/1975	S5.5e: Zr 1	Ake (1979)
14/11/1976	SC3e Zr 0.5	Ake (1979)
18/10/1977	SC8/8.5e	Keenan & Boeshaar (1980)
29/10/1978	SC7/9-e	Keenan & Boeshaar (1980)
02/08/1979	SC4:/8e	Keenan & Boeshaar (1980)

^{12}CN as well as a few ^{13}CN line identifications from Hinkle et al. (1995) and Lambert et al. (1986, their Fig. 4) are shown, respectively. Wallace & Hinkle (1996) report that “CN is the major contributor to the jumble of lines” in that spectral region (cf. their Fig. 5). The CN lines are much stronger in LX Cyg than in σ^1 Ori, but somewhat weaker than in X TrA. The ^{13}CN lines are weaker in LX Cyg, which suggests that it has a lower ^{13}C abundance than X TrA.

The same spectrum of LX Cyg was analysed by Hinkle et al. (2000), who classified two-micron infrared spectra of long-period variables into five categories according to the strength of

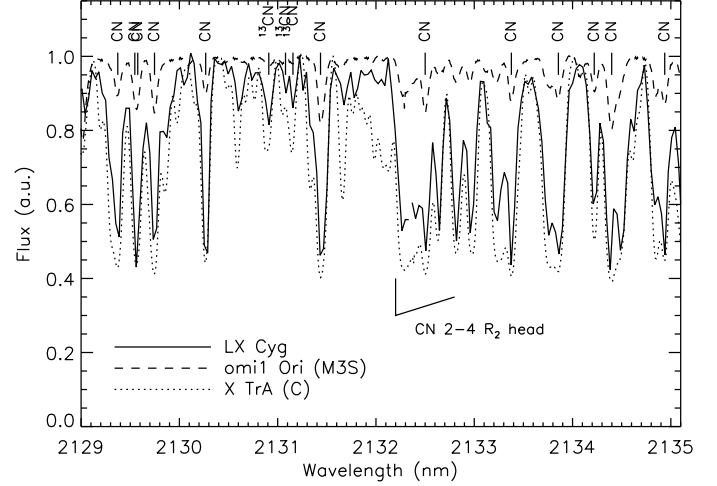


Fig. 8. Comparison of the FTS K-band spectrum of LX Cyg obtained by Dominy & Wallerstein (1987, solid line) with CRIRES-POP (Lebzelter et al., 2012) spectra of the M3S-type giant σ^1 Ori (dashed line) and the C5 carbon star X TrA (dotted line). ^{12}CN line identifications from the Arcturus atlas of Hinkle et al. (1995), denoted as CN, as well as ^{13}CN lines from Lambert et al. (1986) are also shown.

H_2O and CN lines. LX Cyg falls in their category “c”, which equals the C spectral type. The authors also point out occasional surprising differences between the category that they had assigned and the published spectral type, which is obviously also the case for LX Cyg. We thus conclude that it is possible that LX Cyg was already a carbon star at the time of observation by Dominy & Wallerstein (1987) in 1984.

The next spectral observations of LX Cyg were obtained by Joyce et al. (1998) on 16 April 1994 (JD 2449 458). These observations were carried out with the Kitt Peak cryogenic spectrograph (CRSP) in the J band ($\sim 1100 - 1350$ nm) at a resolving power of $R = 1100$. The CRSP spectrum is compared to the NOTCam spectrum obtained on 21 October 2012 in the overlapping wavelength range in the lower panel of Fig. 9. For better comparison, the NOTCam spectrum was convolved with a Gaussian kernel to the CRSP resolving power of $R = 1100$. The agreement between the spectra is very good. The features are essentially the same, small differences such as around ~ 1250 nm may be due to the different pulsation phase at the time of observations or instrumental issues (e.g. flat-fielding). Longwards of 1330 nm, the slight mismatch between the spectra probably is due to telluric absorption by H_2O . One noteworthy difference between the spectra is the H Paschen β line, which appears in emission in the NOTCam spectrum. This is in agreement with the fact that other H lines are also in emission around maximum light; cf. Fig. 7.

Molecular features that dominate the J band of S-type stars are identified by Joyce et al. (1998) as due to TiO , VO , ZrO , ZrS , TiS , H_2O , CN, as well as unidentified features, whereas C-type stars show only bands of the CN red 0-0 system. Positions of bands typical for the S-type stars are indicated in Fig. 9, however, these bands appear to be absent from both spectra. This also holds true for the original, non-convolved NOTCam spectrum shown in the upper panel of Fig. 9.

The CRSP spectrum of LX Cyg was also compared to spectra from SC and carbon stars obtained by Joyce et al. (1998). A comparison with the C star SS Vir and the SC star R CMi is shown in the upper and lower panel of Fig. 10, respectively. The

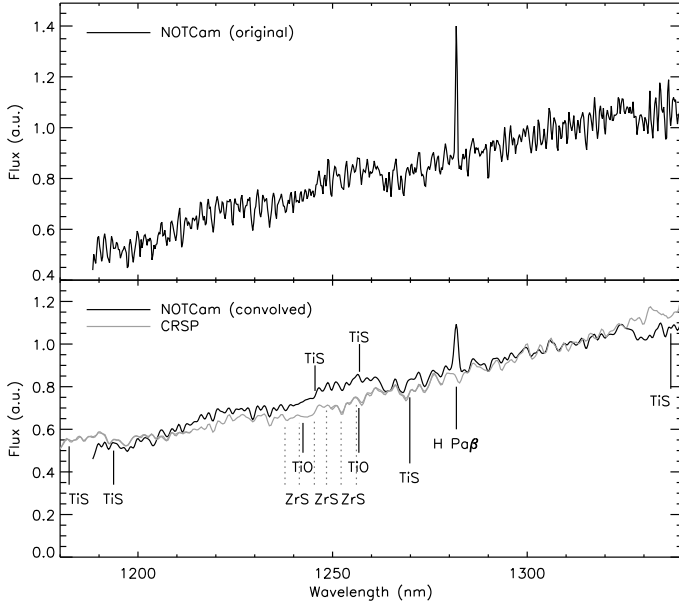


Fig. 9. Upper panel: original NOTCam spectrum of LX Cyg at a resolving power of $R = 2500$. Lower panel: The CRSP (Joyce et al., 1998) and convolved NOTCam J-band spectrum of LX Cyg. Positions of molecular band heads, as identified by Joyce et al. (1998) to be typically present in S-type stars, are indicated. Also the H Pa β line at 1282 nm is indicated, which appears in emission in the NOTCam spectrum taken close to maximum visual light.

differences between the spectra are rather subtle. There might be a feature around 1210 nm in SS Vir that is weaker or not present in LX Cyg and R CMi. Joyce et al. (1998) mention that this feature could be the R head of the C₂ Phillips 0 – 0 band, but they did not find convincing evidence for its presence in the higher-resolution spectra of the carbon stars. One also needs to keep in mind the limited self-similarity of spectra of LX Cyg taken at different pulsation phases; cf. Fig. 9. We conclude that the J band alone is not suited to clearly distinguish between SC- and C-type stars and that the exact spectral subtype of LX Cyg in 1994 is unclear, although it was not of type S.

Zijlstra et al. (2004) report observations of LX Cyg in 2003, when it was claimed to have been of spectral type SC. Unfortunately, no figure of that spectrum is shown and the data are not available, so we are unable to compare to them.

Spectral type determinations in the 1960s and earlier report that bands of LaO were present, and sometimes even strong. These bands seem to be absent in the 1970s, while ZrO was weakly present then. C₂ lines were weakly present in 1978. In particular, all spectral type determinations up to 1975 are S, whereas they are SC from 1976 onwards. The observations available after 1979 are not conclusive enough to constrain the spectral type evolution. The new data presented here suggest that LX Cyg is a C-type star since 2008, when it was observed by *Spitzer*. This means that the evolution from S to C type was completed within 33 years between 1975 and 2008. Within roughly the same period of time, the pulsation period increase happened simultaneously, strongly suggesting a causal connection between these two phenomena.

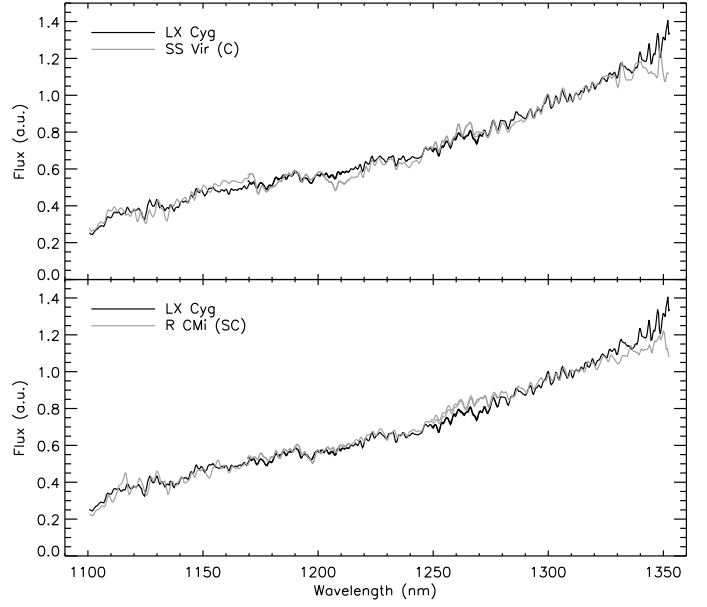


Fig. 10. Comparison of the CRSP J-band spectrum of LX Cyg to the carbon star SS Vir (top) and the SC-type star R CMi (bottom), obtained by Joyce et al. (1998) in 1994.

4. Discussion

The observational evidence suggests that the pulsation period and spectral type of LX Cyg changed in parallel. A similar evolution has been previously observed in the Mira BH Cru (Lloyd Evans, 1985; Whitelock, 1999; Zijlstra et al., 2004; Uttenthaler et al., 2011), therefore, we may refer to this as the BH Cru phenomenon.

The hypothesis usually put forward to explain period changes of Mira stars is that of an onset of a thermal pulse (Wood, 1975; Wood & Zarro, 1981). However, the rate of period change that one would expect from a TP is much lower than observed in a BH Cru phenomenon. Also, at the onset of a TP, the period is expected to decrease because of the initial drop in luminosity caused by switching off the H-burning shell. During no phase of a TP is such a strong period increase expected as is observed in LX Cyg. Also, this scenario does not explain the observed spectral evolution.

Zijlstra et al. (2004) discuss the evolution of BH Cru and put forward another hypothesis. They suggest that the spectral changes are caused by a decrease in stellar temperature (by ~ 200 K), related to the increasing radius. They also suggest that the evolution is unlikely to be related to an ongoing TP, for similar arguments as above. Rather, they speculate that Mira periods may be intrinsically unstable for $C/O \approx 1$, possibly because of feedback between the molecular opacities, pulsation amplitude, and period. Most importantly, Zijlstra et al. (2004) refute that the C/O ratio changed in BH Cru. From this hypothesis one may however expect that some C-type stars can evolve back to the S/SC type, which has never been observed. Also, the temperature variability of a Mira may well exceed 200 K during one pulsation cycle; for instance, Loidl et al. (2001) find $\Delta T_{\text{eff}} = 400$ K for BH Cru. This should induce the same spectral changes as the mechanism put forward by Zijlstra et al. (2004) unless some of the involved molecular reaction rates are sufficiently slow so that the feedback mechanism takes a few pulsation cycles.

Here, we follow a different hypothesis to explain the observed behaviour, which was first proposed by Whitelock

(1999). We suggest that the period increase and spectral evolution of LX Cyg are the result of a 3DUP event that commenced in the 1970s, which brought up an amount of ^{12}C from the interior of the star to its atmosphere. This raised the C/O ratio above unity and the star's atmosphere became carbon rich. The genuine change in abundances led to a change of the spectral appearance of the star because of the new molecular equilibrium in the stellar atmosphere. At the same time as changing the spectral type, the altered (enhanced) molecular opacity also influenced the stellar radius, which led to an increase of the pulsation period on a much shorter timescale than could be accomplished by the TP alone. The linear pulsation models presented in Lebzelter & Wood (2007) indicate that indeed the pulsation period increases when the chemistry changes from oxygen rich to carbon rich at a given luminosity.

The proposed scenario suggests that the spectral type and pulsation period change are causally connected by the 3DUP event. It naturally explains both the spectral changes and the period increase observed in BH Cru and LX Cyg and avoids the problems of the alternative scenarios discussed above. According to current evolutionary models of the TP-AGB, the TP preceding the 3DUP event must have happened several hundred years ago (Herwig, 2005, ; Cristallo, private communication). The time span of visual and photometric observations for LX Cyg is not long enough to identify the slow period decrease expected after the onset of the TP on top of the fast evolution induced by the 3DUP event.

A statistical argument may speak against the 3DUP hypothesis. Not many SC-type stars are known, and out of this small sample two stars must be explained in this way when the expected time span between two TPs (and 3DUP) may be 50 000 to 70 000 years for a plausible mass of $1.5 M_{\odot}$ (Vassiliadis & Wood, 1993). This would not be very likely to observe. On the other hand, a similarly rare event is that of a very late thermal pulse, of which two, possibly even three examples are known (Miller Bertolami et al., 2011).

The upper limit of 33 years on the time it took for the spectral type change may be compared to theoretical calculations of the time it takes to complete a full 3DUP event. The timescale for this is governed by the velocity with which the lower boundary of the convective envelope advances towards the core of the star. Once the intershell material is swept up by the convective envelope, it can be assumed to be mixed throughout the convective envelope very quickly (i.e. within a few years) because the velocity of the convective mixing is very fast, a few km s^{-1} . In the $3 M_{\odot}$ model considered by Mowlavi (1999), it takes ~ 120 years for the surface carbon abundance to reach its asymptotic value after the 3DUP; see their Fig. 7. However, the change in C surface abundance by one 3DUP event may be much larger than that required for an S/SC star with C/O very close to unity to convert it to a carbon star. Hence, our observations do not necessarily contradict these theoretical considerations. This could also mean that the C surface abundance of LX Cyg is still on the rise and the 3DUP event still ongoing.

In principle, it would be desirable to measure the C/O ratio as a function of time to elucidate the reason for the changes of period and spectral appearance of the star. However, there are at least three obstacles that prevent us from doing so:

1. Limitation by the data. Historical data are either not available or the spectral resolution and observed features do not allow for a reliable abundance determination.
2. Limitation by the variability of the star. LX Cyg is a Mira variable with a very complex atmosphere and spectrum

caused by the strongly pulsating atmosphere. Hydrostatic models are not suited for its analysis.

3. Limitation by the models. Hydrodynamic model atmosphere such as those from Höfner et al. (2003) are available only for a few parameter combinations. These models of pulsating, carbon-rich giants are not intended, optimised, or tested for abundance determinations.

We tried to constrain the present-day C/O ratio of LX Cyg from our spectra, however, it was impossible to achieve satisfying fits to any of the C/O-sensitive spectral features with the help of hydrostatic model atmospheres. Estimates of C/O ratios for SC-type stars were given in some of the older papers. Ake (1979) measured a C/O abundance index of 5 and 6 from his two observations of LX Cyg, respectively. On his abundance scale, this corresponds to $\text{C/O} > 0.95$ and ~ 1 (his Table 4). On the other hand, Keenan & Boeshaar (1980) assign a C/O abundance index of 8 – 9, which corresponds to a C/O ratio of 1.00 – 1.02 (Table 2).

5. Conclusions

We present spectral observations of the Mira variable LX Cyg that cover a wide range in wavelength and several years in time. We also discuss period determinations of the star from the literature and complement this with an analysis of recent AAVSO observations. Our own spectra and spectra available from the literature are analysed to follow the spectral type change of LX Cyg. From this we conclude that:

The pulsation period of LX Cyg was stable at ~ 460 d until 1975 when a marked period increase of nearly 25% commenced that lasted up to 1995, after which it stabilised at ~ 580 d. In parallel to the period increase, the spectral type changed from S via SC to C. The available data do not well constrain when the spectral type change happened, but a *Spitzer* IRS spectrum from 2008 suggests that LX Cyg was a carbon star at that time. Our spectral monitoring reveals that the star is of spectral type C during a whole pulsation cycle. The carbon star nature of LX Cyg is corroborated by detailed comparisons with SC and C star spectra available in the literature. The *Spitzer* IRS spectrum suggests that SiC grains are present in the circumstellar environment of LX Cyg, possibly also PAHs. Also, the spectral energy distribution and IR colours suggest that dust is present around the star.

The scenario of a recent 3DUP event presents a natural explanation for both the spectral change and the period increase by the altered molecular equilibrium and opacity by adding ^{12}C to the atmosphere of the star. Both a recent thermal pulse as well as a simple decrease in surface temperature do not satisfactorily explain the observations. Finally, we conclude that LX Cyg is a rare case of a star where we can see AGB stellar evolution in real-time and that the study of its general properties and evolution may lead to unique insights into the transition from oxygen rich to carbon rich stars on the AGB, which deserves further observations.

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